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THE DESIGN OF A THERMALLY EFFICIENT 1:256

KU-BAND FEED NETWORK FOR A MMIC PHASED ARRAY

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THE DESIGN OF A THERMALLY EFFICIENT 1:256
KU-BAND FEED NETWORK FOR A MMIC PHASED ARRAY*

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ABSTRACT

A thin, thermally transparent, 1:256 corporate feed network
for use in a GaAs MMIC Ku-Band phased array antenna has been
designed. The network will be realized using a recently developed
RF transmission medium called CHANNELINE. CHANNELINE consists of a
core of TFE coated copper wire placed in a channel routed through a
heat exchanging metal structure which composes the backside of the
array. This unique packaging arrangement conserves both volume and
weight while simultaneously allowing the rapid transfer of
internally generated heat. The network is comprised of a 1:4
waveguide to CHANNELINE divider, four 1:16 microstrip/CHANNELINE
dividers, and sixty-four 1:4 microstrip dividers. The final 1:4
divider is colocated in the module with the GaAs MMIC elements.
This network is expected to realize better than 15 dB of return loss
with less than 1.3 dB insertion loss over an 8% bandwidth. Finally,
the current status of array hardware is presented.

Table I.   Ku-Band Phased Array

PRELIMINARY DESIGN GOALS

1. R/T Mode   :   Half Duplex, 100% Tx Capability
2. RF Bandwidth   :   8% at Ku-Band
3. Tx Power   :   1.0 watt per element
4. Input RF Rx Drive Power   .   0.1 watt
5. Noise figure   :   4.0 dB
6. Array geometry   .   256 elements, triangular lattice
7. Phase/Amplitude control   :   16 bit complex weight
8. LNA burn-out   :   0.1 watt per element, up to 40 GHz
9. Polarization   :   RHCP
10. Scan angle   :   EL + 60°, AZ + 60°
11. Control feed technology   :   High speed serial data
12. Update rate   :   10000/sec
13. DC Power available   :   1.3 kW
14. Environment   .   100% Relative Humidity, radome
15. Cooling   :   Forced convection, air or liquid
16. Platform   :   F-15, F-16

Introduction

At this writing, aerospace phased array antenna opportunities exist throughout the UHF, microwave, and millimeter wave frequency bands. From the Global Positioning System (GPS) at 1.2 GHz to Milstar at 44 GHz, phased arrays are being applied to solve today's airborne communication problems.

These efforts, coupled with the growing interest in monolithics, spawned an internally funded technology development project: To design and develop a controlled high performance monolithic phased array. Ku-Band was selected for the center frequency. This choice represents a compromise between the UHF band, which does not lend itself to monolithics technology, and millimeter wave band, in which MMIC technology is yet under-developed. The Ku-Band also allows the design to incorporate conventional hybrid technology as well. Table I lists the set of preliminary design specifications for this research and development array.

Conceptual Design

The conceptual array is illustrated in Figure 1. The two hundred and fifty-six (256) circular elements which comprise each subarray are arranged in a square shape with each row being offset one-half element from surrounding rows. This triangular lattice of elements is preferable to a square one for several reasons. Classic analysis shows that equivalent gain and scan angle can be achieved
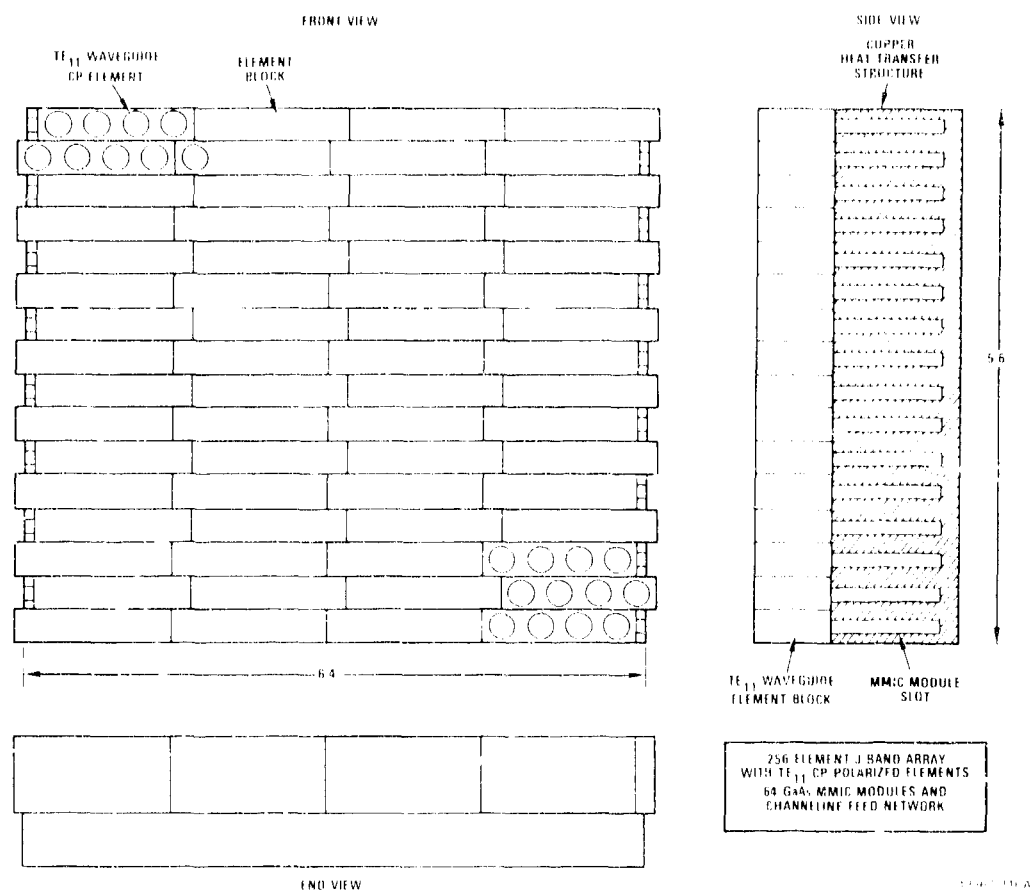
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Figure 1. Front, Side and End Views of the Array
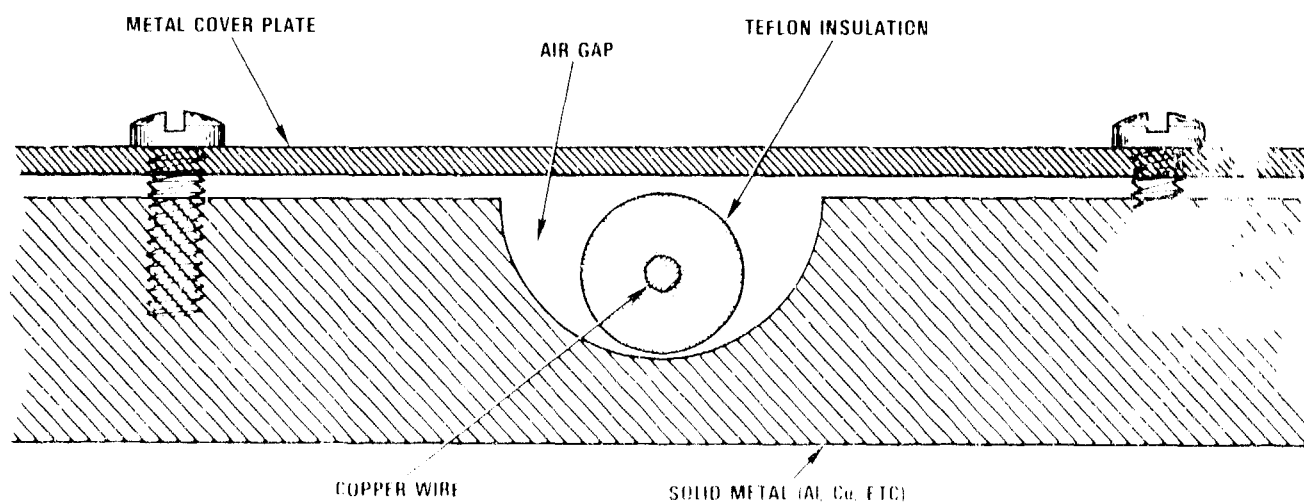
CROSS SECTION OF CHANNELINE ASSEMBLY

Figure 2. CHANNELINE Cross Section with Exaggerated
Air Gap and Loose Cover Plate

with 16% fewer elements[1]. In arrays requiring several subarrays of this type (e.g., a 4096 element array composed of 16 subarrays), significant cost, weight, and volume reduction is realized. The concept of modular packaging is incorporated to permit quick and easy repair or replacement of any 4-element block or 256 element subarray.

In the event of a "stand-alone" application, a more circular array face would be used to aid sidelobe performance.

RF Corporate Feed Network

Presently, GaAs FET and MMIC technology is sufficiently advanced to allow the transmit array to operate at 15 GHz with a 100% duty cycle and one watt (1 W) of radiated power per element. For a 256 element array, approximately 1 kW of power would be generated within the array, most of it in the MMIC module and power amplifier directly behind the radiating structure. This configuration is shown in the side view of Figure 1. Since the array measures a mere eight inches (8.0") on a side, it must be capable of dissipating at least 15.6 W/in^2.

The problem, then, is how to conduct the heat away from the RF circuitry and into a heat exchanger on the backside of the array. Typically, the corporate feed network or beam former is located between the heat source and desired sink. Regardless of the type of feed network used, (i.e., microstrip, stripline, or waveguide) thermal conduction is impeded. The solution: A microstrip and coaxial transmission line feed network realized using
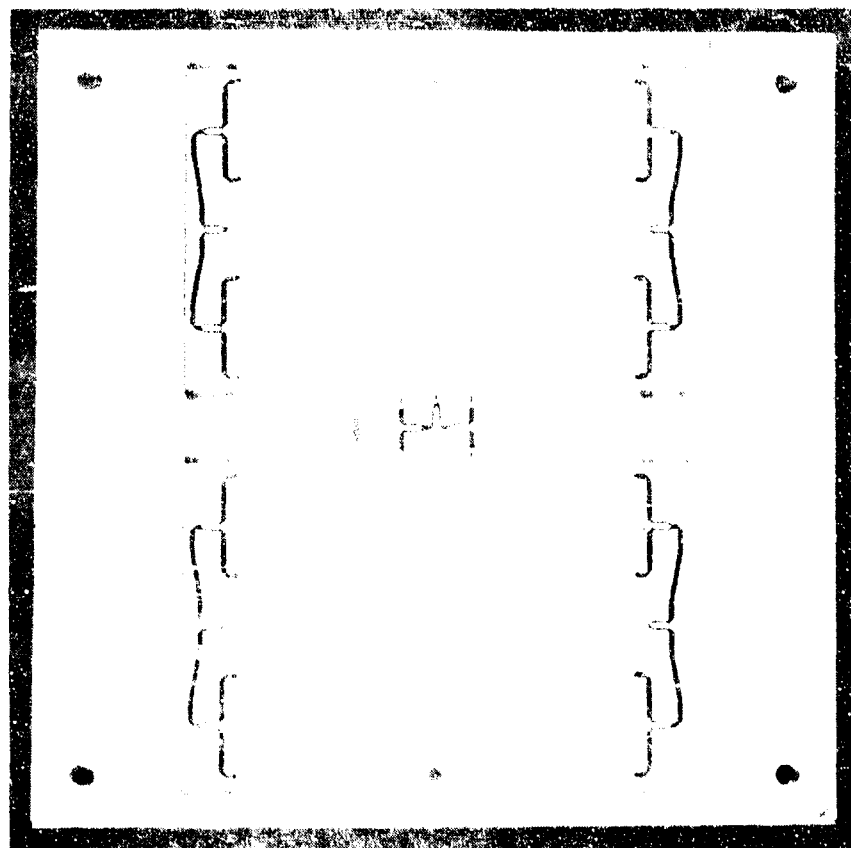
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Figure 3a.   Front View of CHANNELINE 1:16 Divider Assembly
(Backside of Array)
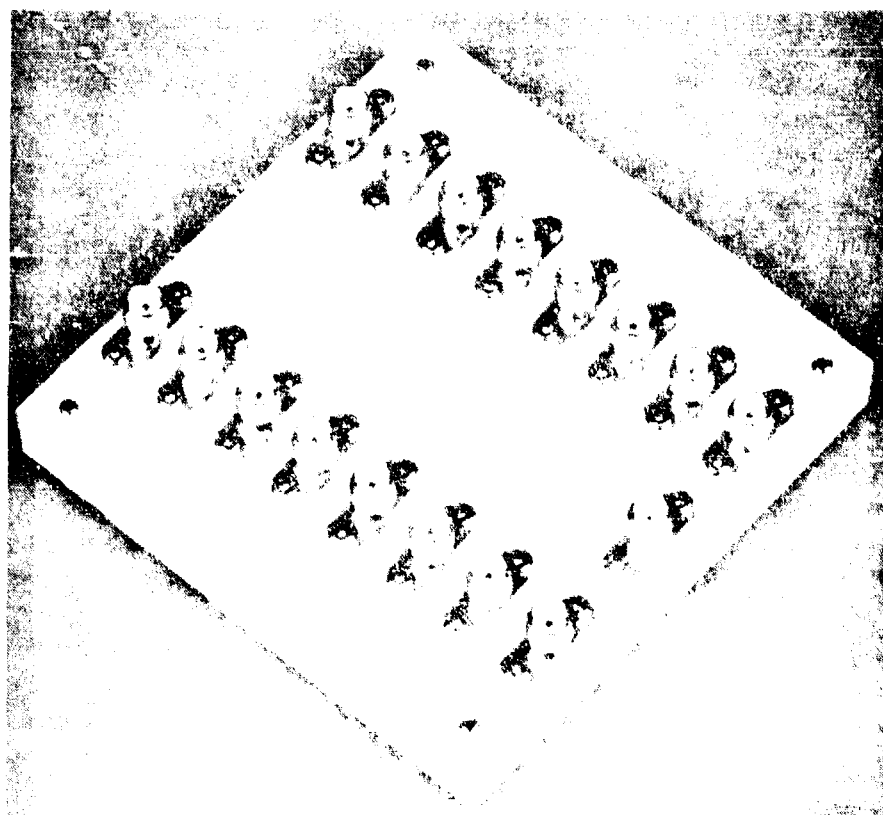
a recently developed RF transmission medium called CHANNELINE.
CHANNELINE consists of a single strand of TFE coated copper wire
placed in a channel routed through a heat exchanging metal structure
which composes the underside of the array. A cross-sectional view
of this structure is shown in Figure 2. This structure supports
quasi-TEM mode wave propagation. Note the air gap around the Teflon
insulation near the cover. It is this gap that causes the
dielectric medium to be slightly inhomogeneous, which in turn
prevents it from supporting pure TEM waves[2].

The CHANNELINE connects the miniature precision thin film
microstrip divider circuits located in cavities hollowed out of a
thermally conductive backplane. Five 1:4 uncompensated Wilkenson
dividers comprise the 1:16 assembly. Figure 3a depicts a frontal
view of the assembly, while Figure 3b shows the output ports of this
breadboard model. By using CHANNELINE transmission lines as the
primary interconnection media within the array backplane, thermal
efficiency is realized. Furthermore, CHANNELINE provides
attenuation versus cross-sectional area performance comparable to
waveguide without the interconnection headaches typically caused by
the lack of available volume near the array face. This arrangement
allows maximum use of the lower loss CHANNLELINE (0.03 dB/cm at
15 GHz) and minimum use of the higher loss per unit length
microstip. The result is that approximately 88% of the divider
structure is left available for unimpeded heat transfer. Circuit
performance characteristics are shown in Figure 4.

1:16 CHANNELINE/MICROSTRIP
POWER DIVIDER ASSEMBLY
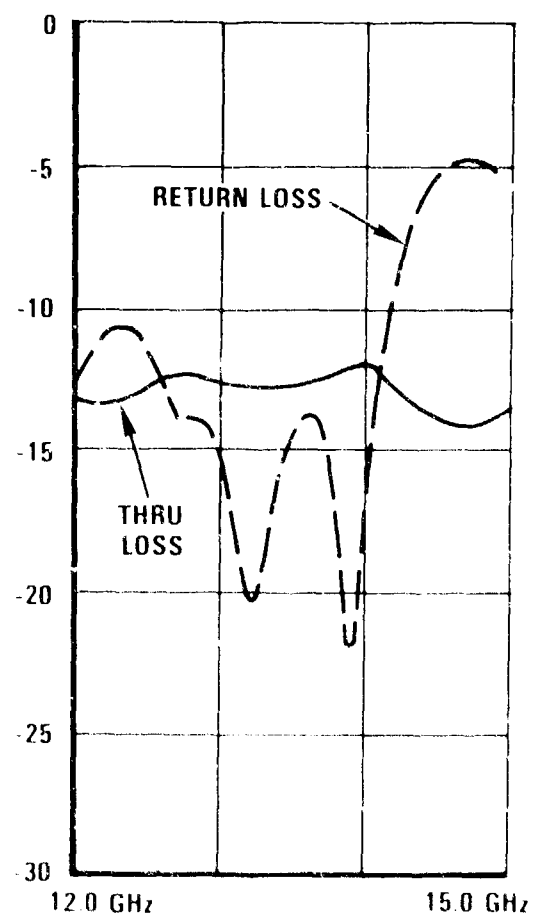
PERFORMANCE   ISOLATION
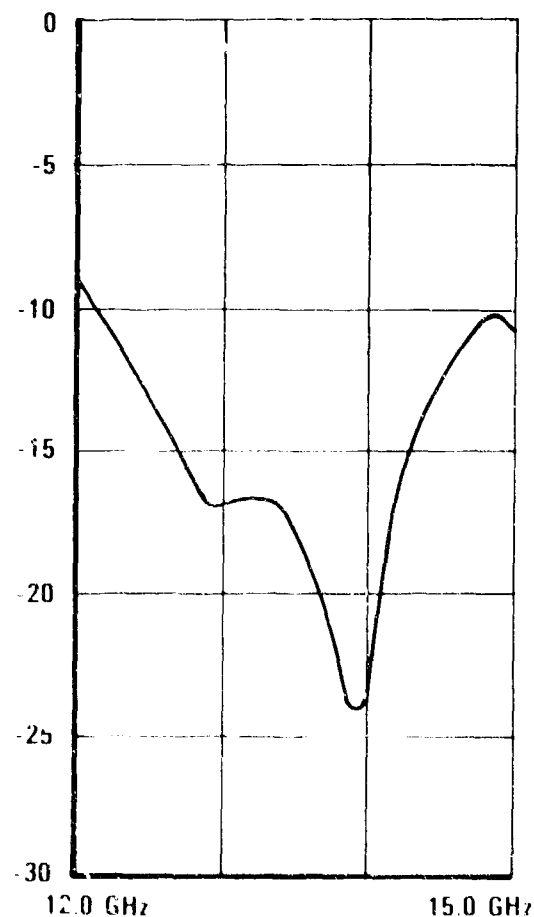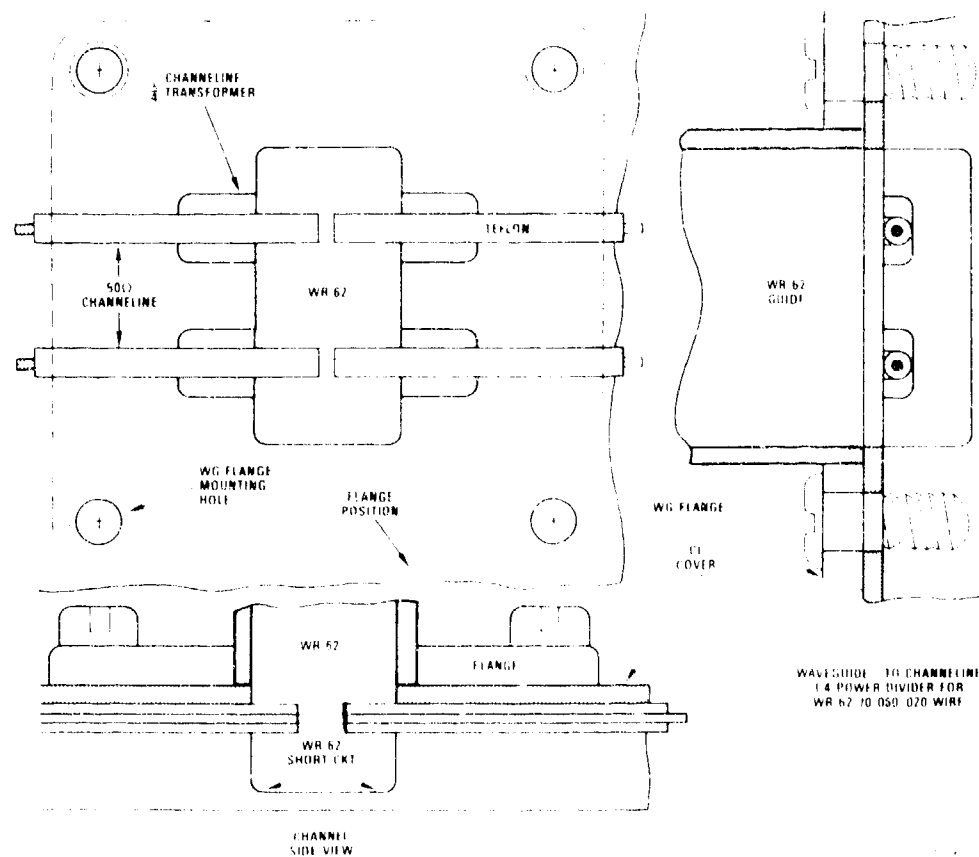

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Figure 4.

Figure 5.

Figure 6.

In the event of the 256 element assembly being a subarray of a larger antenna, the initial waveguide feed would interface with waveguide power divider prior to the CHANNELINE split. Because efficient heat transfer is accomplished at the subarray level, the longer runs required in a corporate feed network for the larger array can be built in full size waveguide for minimum attenuation. Primary amplitude taper, if required, could be incorporated in the waveguide splitter.

The corporate feed network for the 256 element array begins with a 1:4 waveguide to CHANNELINE divider. It is similar to a standard waveguide-to-coaxial adapter with the addition of a coaxial reactive 1:4 power divider. A cross-sectional view is shown in Figure 5. Impedance matching is accomplished by properly positioning the probes within the guide and/or by the use of quarter wavelength transformers in CHANNELINE.

A scale model breadboard was built at 10.5 GHz using WR 90 waveguide and 0.141 inch semi-rigid coaxial cable to simulate CHANNELINE. This model did not have the quarter wavelength matching transformers, rather, impedance matching was achieved by probe positioning only. As shown in Figure 6, a sliding waveguide short circuit was used to tune the transition. Insertion loss, return loss and isolation versus frequency for the circuit configuration are given in Figures 7 and 8. Although an optimum design has not been realized, these waveguide power divider experiments have

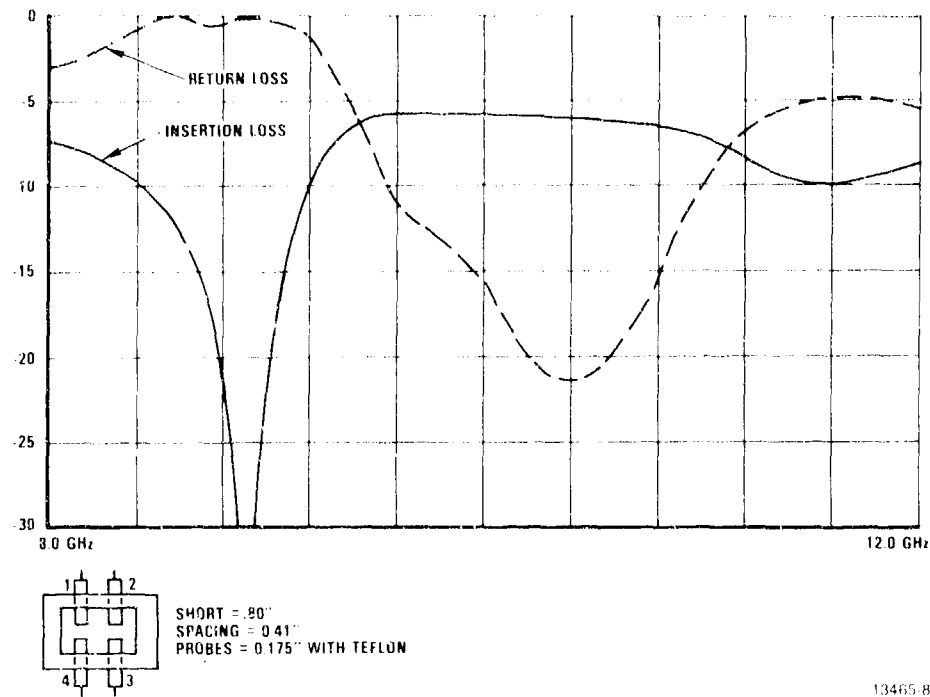## WAVEGUIDE TO CHANNELINE 1:4 DIVIDER
PERFORMANCE

SHORT = .80"
SPACING = 0.41"
PROBES = 0.175" WITH TEFLON

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Figure 7.

ISOLATION FOR WAVEGUIDE TO CHANNELINE 1:4 DIVIDER

SHORT = 0.80
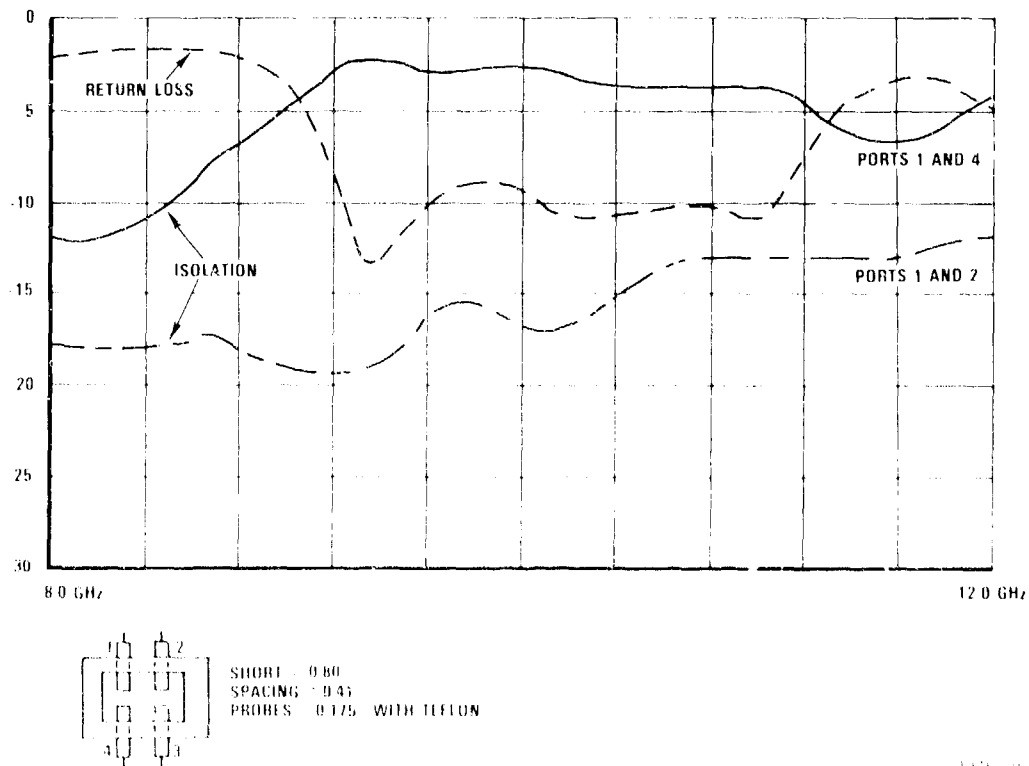SPACING = 0.45
PROBES = 0.175 WITH TEFLON

Figure 8.

demonstrated the feasibility of a simple, low loss waveguide to CHANNELINE 1:4 divider for the array-to-waveguide I/O interface.

The final 1:4 microstrip divider is colocated with the GaAs MMIC and housed in a Kovar module. There it is perpendicular to the thermal path, thus, it does not restrict heat flow.

In summary, the entire 1:256 feed network is comprised of A) a 1:4 waveguide to CHANNELINE divider, with each of its four CHANNELINES running to B) a 1:16 thermally efficient microstrip/CHANNELINE assembly whose 64 output ports each feed C) a final 1:4 divider which precedes the GaAs MMIC circuitry and the final radiating element. This rather complicated arrangement is clearly illustrated in Figure 9.
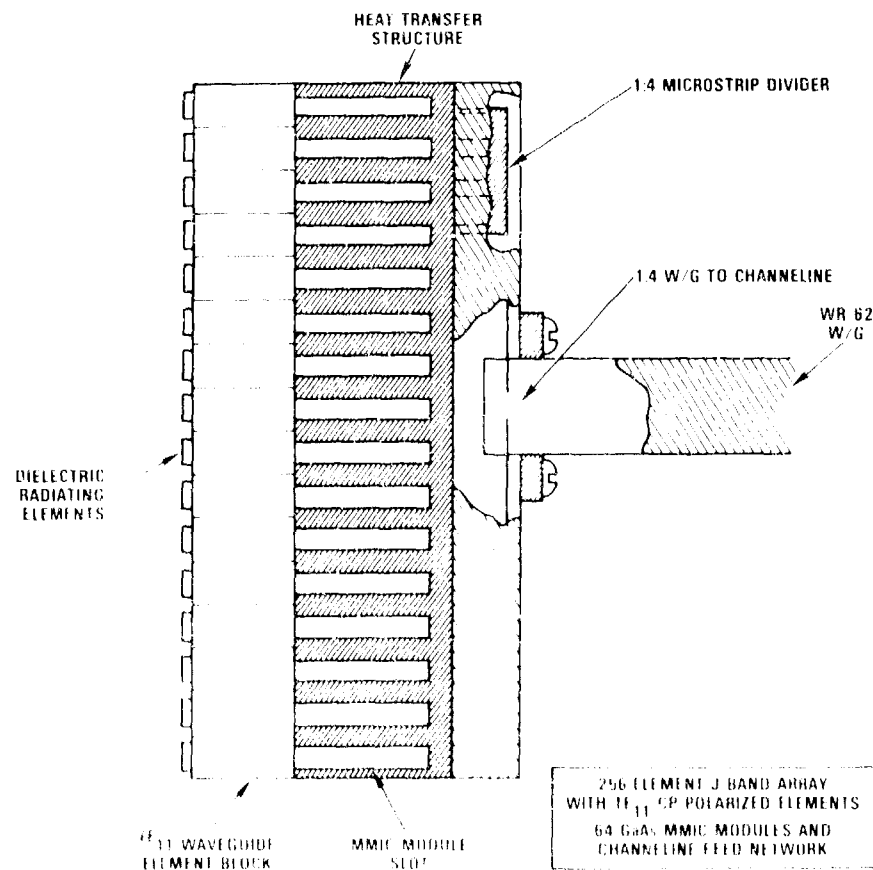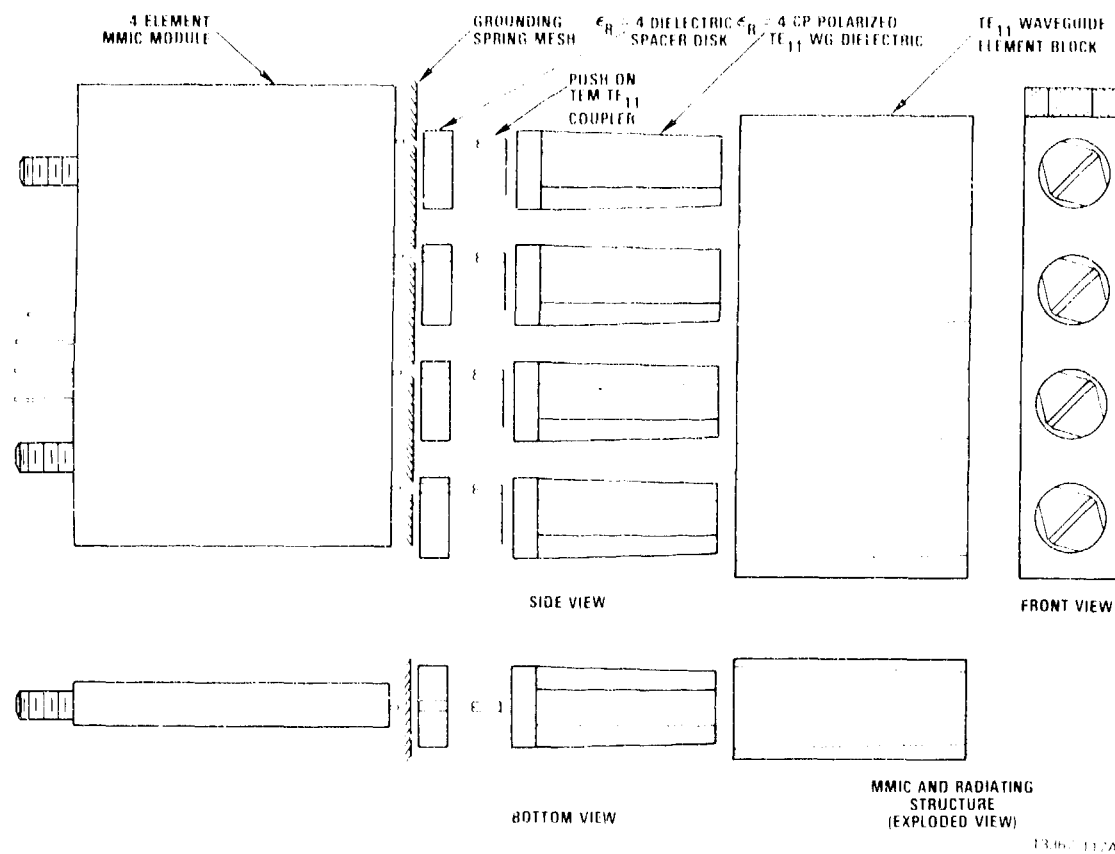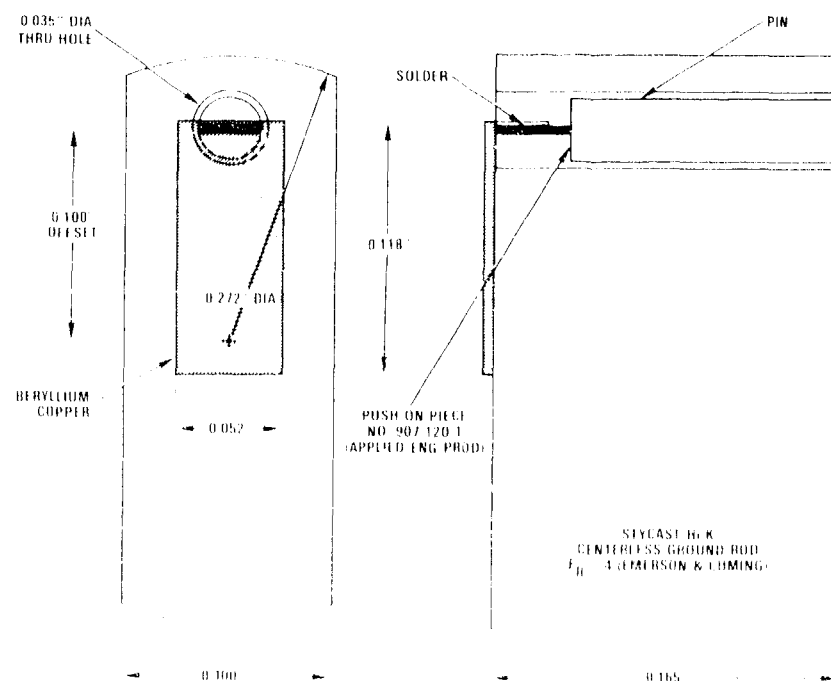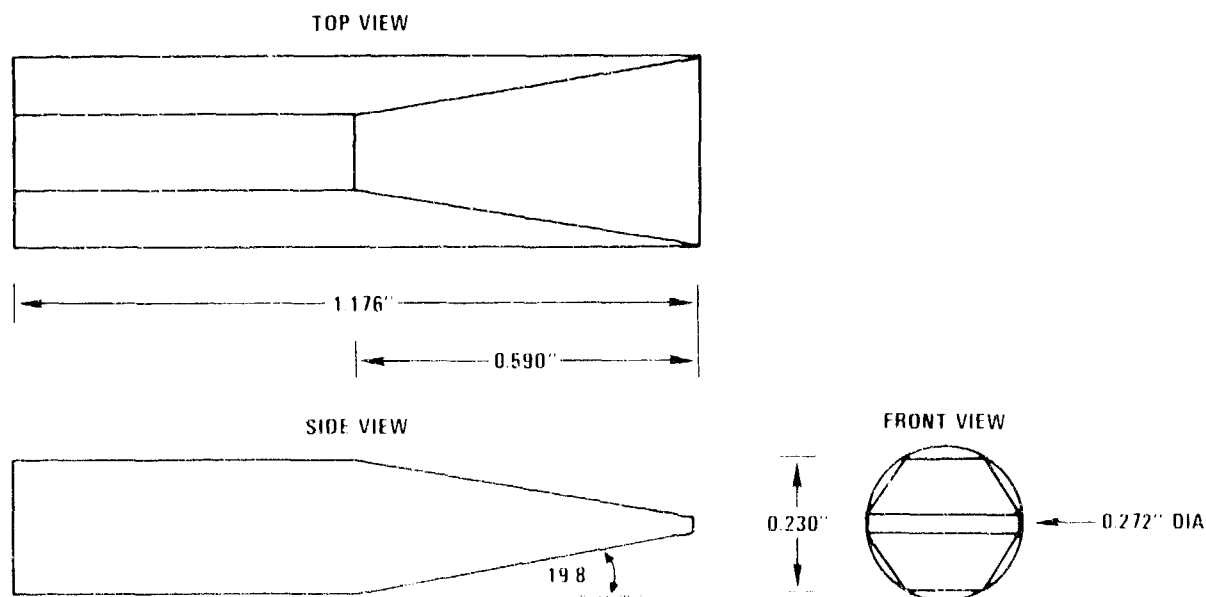

Figure 9.

Figure 10.

WAVEGUIDE EXCITATION STRUCTURE

Figure 11.

50

Waveguide Radiation Element

The MMIC, radiation element, and circular waveguide block are shown in the exploded view of Figure 10. The actual radiating structure is shown in Figure 11. The circular waveguides have a coaxial pin launch at the module end. The cavity is filled with a dielectric transformer at the waveguide to free space interface. These "plug-in" dielectric radiating elements can be designed to produce either a linearly or circularly polarized antenna (Figure 12). An element test fixture using a 50 ohm glass-to-metal seal with an SMA push-on connector was developed to simulate the MMIC module/waveguide interface while testing the dielectric elements. Figure 13 is a photograph of this fixture with a linearly polarized element installed. The glass/metal seal is under the SMA launch.
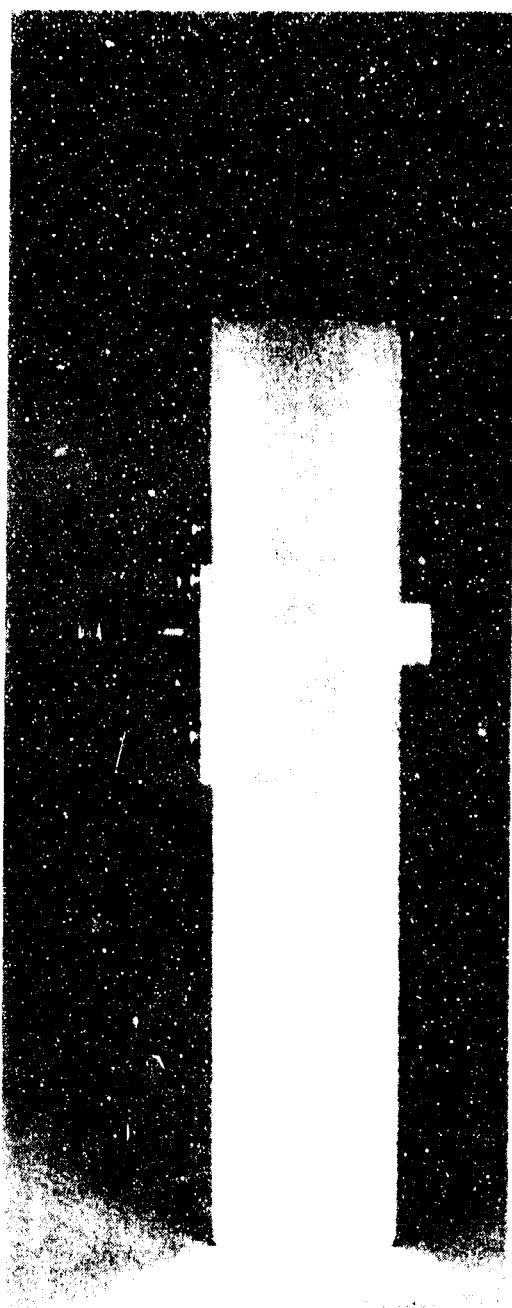
RADIATING PIECE FOR CIRCULAR POLARIZATION

TOP VIEW

1.176"

0.590"

SIDE VIEW

FRONT VIEW

0.230"

0.272" DIA

19.8

13465-4

Figure 12.

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Figure 13. Radiating Element Test Fixture with
Linearly Polarized Element Installed

GaAs MMIC

The monolithic section of this phased array is also currently under development. A conceptual design is shown in Figures 14 and 15. The microstrip 1:4 divider passes the RF signal into a monolithic complex weight which feeds a GaAs FET power amplifier. In the receive mode, the incoming signal would encounter an LNA prior to being weighted and combined. On the digital side, a subgigabit rate serial control line made of miniature (Zo = 75 ohm) CHANNELINE is run into each module. This line feeds a high speed serial-to-parallel demultiplexer which also resides in the module. In this way, control wiring is minimized and precious area is conserved. These circuits, housed in a Kovar box, will perform all signal amplitude and phase control. They will also generate most of the heat which must be dissipated.

Initial thermal analysis indicates that the metal (copper or aluminum) comb/CHANNELINE heat transfer structure can be sufficiently cooled with either forced convection of air (if a finned heat sink is incorporated) or liquid (with no finned sink required). "Sufficiently cooled" may be defined as keeping the internal module temperature at less than 100°C. Electrically, this represents a viable operating temperature. Mechanically, it also ensures that the cooling liquid will not boil since the external wall of the structure must, by definition, be cooler than the internal comb and therefore operate at less than 100°C.
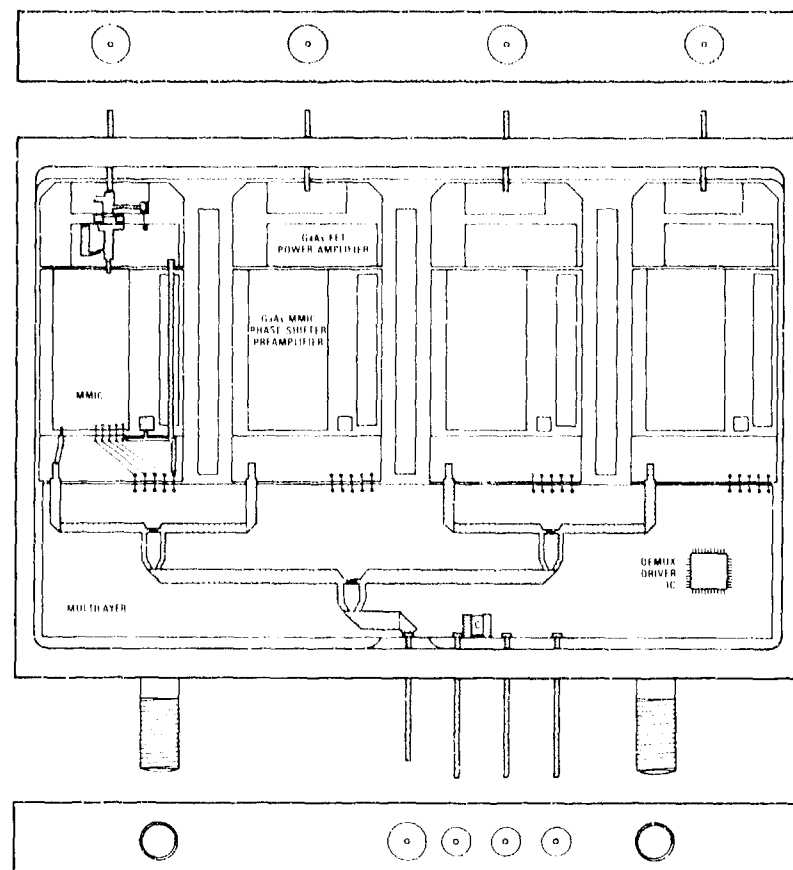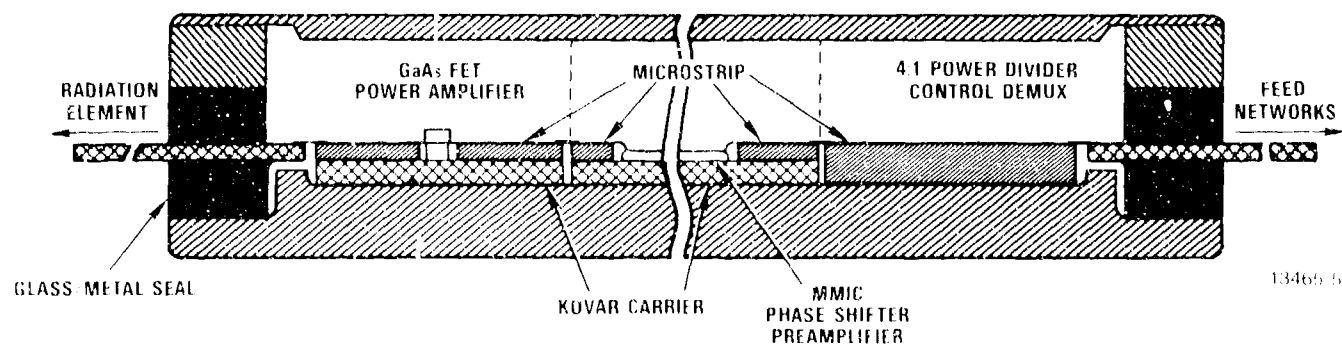
Figure 14.

KU-BAND ARRAY
MONOLITHIC MODULE

Figure 15.

Conclusion

Phased arrays are in demand because of their versatility. GaAs MMIC's are also on the rise due to their size, weight, performance, and power consumption aspects. The mating of the two is a natural step in the progression towards smaller, lighter, and leaner phased arrays. Monolithic LNA's, FET power amplifiers, phase shifters, and complex weights, placed directly behind the antenna aperture, can greatly improve overall performance. Packaging technology must keep pace.

The design status of a 1:256 Ku-Band feed network has been presented. The assembly employs a newly developed RF transmission medium called CHANNELINE. Its size and thermal properties make it ideal for conserving both volume and weight while simultaneously allowing the rapid dissipation of internally generated heat. By blending this technology with existing hybrid and waveguide approaches, the heat transfer and packaging problems associated with small, high power, MMIC controlled phased arrays may be more readily overcome.

REFERENCES

[1] Skolnik, Merrill I. (1970) Radar Handbook, McGraw-Hill, New York, p. 11-19

[2] Paul, Clayton R. and Nasar, Syed A. (1982) Introduction To Electromagnetic Fields, McGraw-Hill, New York, p. 335